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LASER SURGERY IN OTOLARYNGOLOGY:

BASIC PRINCIPLES AND SAFETY CONSIDERATIONS

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INTRODUCTION

Laser light is the brightest monochromatic (single color) light existing today. Besides being a standard tool of the research lab, the laser is currently used in communications, surveying, manufacturing, diagnostic medicine and surgery. Supermarket bar code scanners and the compact disk player have even moved lasers into everyday life. The addition of lasers and the development of new lasers to the surgical armamentarium in otolaryngology--head and neck surgery offers new and exciting possibilities to improve conventional techniques and to expand the scope of this specialty.

The purpose of this chapter is to review the principles, applications, and safety considerations associated with the use of lasers in the upper aerodigestive tract. It is hoped that the material presented here will provide a foundation upon which the otolaryngologist--head and neck surgeon can begin to apply this exciting technology in his daily practice.

LASER BIOPHYSICS

Laser is an acronym for *l*ight *a*mplification by the *s*timulated *e*mission of *r*adiation. Albert Einstein postulated the theoretical foundation of laser action, stimulated emission of radiation, in 1917. In his now classic publication, "*Zur Quantum Theorie der Strahlung*" ("The Quantum Theory of Radiation") he discussed the interaction of atoms, ions, and molecules with electromagnetic radiation (Einstein, 1917). He specifically addressed absorption and spontaneous emission of energy and proposed a third process of interaction: stimulated emission. Einstein postulated that the spontaneous emission of electromagnetic radiation from an atomic transition has an enhanced rate in the presence of similar electromagnetic radiation. This "negative absorption" is the basis of laser energy.

Many attempts were made in the following years to produce stimulated emission of electromagnetic energy, but it was not until 1954 that this was successfully accomplished. In that year, Dr. Charles Townes and two of his students discussed their experiences with stimulated emission of radiation in the microwave range of the electromagnetic spectrum. This represented the first *maser* (*m*icrowave *a*mplification by the *s*timulated *e*mission of *r*adiation) and paved the way for the development of the first laser.

In 1958, Dr. Townes and another physicist, Dr. Arthur Schawlow published "Infrared and Optical Masers" (Schawlow and Townes, 1958), in which they discussed stimulated emission in the microwave range of the spectrum and described the desirability and principles of extending stimulated emission techniques to the infrared and optical ranges of the spectrum. Dr. Theodore Maiman expanded on their theoretical writings and built the first laser in 1960 (Maiman, 1960). Using synthetic ruby crystals, this laser produced electromagnetic radiation at a wavelength of 0.69 μm in the visible range of the spectrum. Although the laser energy produced by Maiman's ruby laser lasted less than a millisecond, it paved the way for explosive development and widespread application of this technology.

A laser is an electrooptical device that emits organized light (rather than random-pattern light emitted from a light bulb) in a very narrow, intense beam by a process of optical feedback and amplification. Since the explanation for this organization involves stimulated emission, a brief review of quantum physics is necessary.

In the semi-classical picture of the atom, each proton is balanced by an electron that orbits the nucleus of the atom in one of several discrete shells or orbits. A shell corresponds to a specific energy level and these energy levels are characteristic of each different atom or molecule. The smaller shells, where the electron is closer to the nucleus,

have a lower energy than the larger shells, where the electron is farther away from the nucleus. Electrons of a particular atom can only orbit the nucleus at these levels, or "floors." Radiation of energy does not occur while the electrons remain in any of these shells.

Electrons can change their orbits or energy levels, thereby changing the energy state of the atom. During excitation, an electron can make the transition from a low energy level to a higher energy state. If the excitation comes from the electron interacting with a discrete packet of light (a photon), this is termed absorption. The atom always seeks its lowest energy level, the ground state. Therefore, the electron will spontaneously drop from the high energy shell back to the lowest energy shell in a very short time (typically 10^{-8} s). As the electron spontaneously drops from the higher energy shell to the lower energy shell, the atom must give up the energy difference. The atom emits the extra energy as a photon of light in a process termed the spontaneous emission of radiation (Fig. 1).

Einstein postulated that an atom in a high energy state would be induced to make the transition to a lower energy state even faster than the spontaneous process if it interacted with an existing photon of the same energy. One might imagine a photon colliding with an excited atom and the collision results in two identical photons (one incident and one produced by the decay) leaving the collision. The two photons have the same frequency, have the same energy and are travelling in the same direction in spatial and temporal phase (Einstein, 1917). This process, which Einstein called *stimulated emission of radiation*, is the underlying principle of laser physics (Fig. 1).

All laser devices have an optical resonating chamber (cavity) with two mirrors; the space between these mirrors is filled with a lasing medium such as argon, neodymium:yttrium aluminum garnet (Nd:YAG) or carbon dioxide (CO_2). An external

energy source such as an electric current excites the lasing medium within the optical cavity. This pumping causes many atoms of the lasing medium to be raised to a higher energy state. When more than half the atoms in the resonating chamber have reached a particular excited state, a population inversion has occurred. Spontaneous emission is taking place in all directions; light (photons) emitted in the direction of the long axis of the laser is retained within the optical cavity by multiple reflections off the precisely aligned mirrors. One mirror is completely reflective and the other partially transmissive (Fig. 2). Stimulated emission occurs when a photon interacts with an excited atom in the optical cavity, yielding pairs of identical photons that are of equal wavelength, frequency and energy and are in phase with each other. This process takes place at an increasing rate with each passage of the photons through the lasing medium; the mirrors serve as a positive feedback mechanism for the stimulated emission of radiation by reflecting the photons back and forth. The partially transmissive mirror emits some of the radiant energy as laser light. The radiation leaving the optical cavity through the partially transmissive mirror quickly reaches an equilibrium with the pumping mechanism's rate of replenishing the population of high energy state atoms.[1]

The radiant energy emitted from the optical cavity is of the same wavelength (monochromatic), is extremely intense and unidirectional (collimated), and is coherent both temporally and spatially. *Temporal coherence* refers the waves of light oscillating in phase over a given time interval, Δt. Whereas *spatial coherence* means that the photons are equal

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[1]We have used the term atom in the preceeding discussion when referring to the lasing material. In reality, the lasing material can be molecules, ions, atoms, semi conductors and even free electrons in an accelerator. In these other systems, it does not have to be the bound electron that is excited. It can be many different excitations, including molecular vibrational excitation or the kinetic energy of an accelerated electron.

and parallel across the wave front. These properties of monochromaticity, intensity, collimation and coherence distinguish the organized radiant energy of a laser light source from the disorganized radiant energy of a light bulb or other light source (Ossoff and Karlan, 1985). (see Fig. 3)

After the laser energy exits the optical cavity through the partially transmissive mirror, the radiant energy typically passes through a lens that focuses the laser beam to a very small beam diameter, or spot size, ranging from 0.1 to 2.0 mm. When necessary, the lens system is constructed to allow the visible helium-neon aiming laser beam and the invisible CO_2 or Nd:YAG laser beam to be focused coplanar. The optical properties of each focusing lens determine the focal length or distance from the lens to the intended target tissue for focused use.

CONTROL OF THE SURGICAL LASER

With most surgical lasers, the physician can control three variables: (1) power (measured in watts), (2) spot size (measured in millimeters), and (3) exposure time (measured in seconds). Of these three variables, power is the least useful as a parameter and may be kept constant with widely varying effects, depending on the spot size and the duration of exposure. For example, the relationship between power and depth of tissue injury becomes logarithmic when the power and exposure time are kept constant and the spot size is varied (Ossoff and Karlan, 1985).

Power density (PD) is a more useful measure of the intensity of the beam at the focal spot than power because it takes into account the surface area of the focal spot. Specifically, power density or power per unit area of the beam, expressed in watts per

square centimeter, is a measure of the power output of the laser in watts divided by the cross-sectional area of the focal spot in square centimeters.

$$PD = \frac{\text{power in the focal spot}}{\text{area of the focal spot}}$$

Power and spot diameter are considered together and a combination is selected to produce the appropriate power density. If the time of exposure is kept constant, the relationship between power density and depth of injury is linear as the spot size is varied. Power density is the most important operating parameter of a surgical laser at a given wavelength. Therefore, surgeons should calculate the appropriate power density for each procedure to be performed; these calculations would allow the surgeon to control in a predictable manner the tissue effects when changing from one focal length to another (400 mm for microlaryngeal surgery to 125 mm for handheld surgery) or when using surgical lasers with different transverse electromagnetic modes (TEM_{00} vs TEM_{01}). Power density varies directly with power and inversely with surface area (A). This relationship of surface area to beam diameter is an important when evaluating the power density. The larger the surface area, the lower the power density; conversely, the smaller the surface area, the higher the power density. Surface area is expressed as:

$$A = \pi r^2$$

where r is the beam radius. Since the radius is one-half of the beam diameter (d/2), surface area also can be expressed as:

$$A = \pi d^2/2^2 \text{ or } A = \pi d^2/4$$

Surface area, then, varies as the square of the beam diameter; doubling the beam diameter will increase the surface area by four times, while halving the beam diameter will yield only one-quarter the area. Therefore, power density varies inversely with the square of the diameter. For example, doubling the beam diameter (from d to 2d) reduces the power density to one-fourth (PD to PD/4) and halving the spot diameter (d to d/2) increases power density by a factor of 4 (Ossoff and Karlan, 1985).

Newer CO_2 lasers emit radiant energy with a characteristic beam intensity pattern different from that produced by older-model lasers. Because this beam pattern ultimately determines the depth of tissue injury and vaporization pattern across the focal spot, the surgeon must be aware of the characteristic beam pattern of the laser. *Transverse electromagnetic mode* (TEM) refers to the distribution of energy across the focal spot and determines the shape of the laser's spot. The most fundamental transverse electromagnetic mode is TEM_{00}, appearing circular when cut in cross section; the power density of the beam follows a gaussian distribution, with its greatest amount of energy at the center of the beam, then diminishing progressively toward the periphery. TEM_{01} and TEM_{11} modes are less fundamental modes that have a more complex distribution of energy across their focal spot, causing predictable variations in tissue vaporization depth. Additionally, their beams cannot be focused down to as small a spot size at the same working distance as TEM_{00} lasers (Fuller, 1980).

Although simple ray diagrams normally show parallel light to be focussed to a point, the actual situation a bit more complicated. A lens will focus a gaussian beam to a *beam waist* or a finite size. This beam waist is the minimum spot diameter, d, and can be written as

$$d \sim \frac{2f\lambda}{D}$$

where f is the focal length of the lens, λ is the wavelength of light and D is the diameter of the laser beam incident on the lens (Fig. 4). The beam waist occurs not at one distance from the lens, but over a range of distances. This range is termed the *depth of focus* and can be written as

$$\text{depth of focus} \sim \frac{\pi\, d^2}{2\,\lambda}$$

We realize the depth of focus every time we focus a camera. With a camera, a range of objects is in focus, and we can set the focus without carefully measuring the distance between the object and the lens. Notice from the above equations that a long focal length lens (a large f) leads to a large beam waist. A large beam waist also translates as a large depth of focus.

The size of the laser beam on the tissue (spot size) can therefore be varied in two ways. Because the minimum beam diameter of the focal spot increases directly with increasing the focal length of the laser focusing lens, the surgeon can change the focal length of the lens to obtain a particular beam diameter. As the focal length becomes smaller, there is a corresponding decrease in the size of the focal spot; also, the smaller the spot size is for any given power output, the greater the corresponding power density. The second way the surgeon can vary the spot size is by working either in or out of focus. The minimum beam diameter and highest power concentration occur at the focal plane, where

much of the precise cutting and vaporization is carried out (Fig. 5a). As the distance from the focal plane increases, the laser beam diverges or becomes defocussed (Fig. 5b). Here, the cross sectional area of the spot grows larger and thus lowers the power density for a given output. As one can readily see the size of the focal spot depends on both the focal length of the laser lens and whether the surgeon is working in or out of focus. Fig. 6 demonstrates these concepts using arbitrary ratios accurate for a current model TEM_{00} CO_2 laser. The laser lens setting (focal length) and working distance (focus/defocus) combinations shown here determine the size of the focal spot. The height of the various cylinders represents the amount of tissue (depth and width) vaporized after a 1-second exposure at the three focal lengths.

Varying the exposure time represents the third way in which the surgeon can vary the amount of energy delivered to the target tissue. *Radiant exposure* (RE) refers to the amount of time (measured in seconds) that a laser beam irradiates a unit area of tissue at a constant power density. Radiant exposure is a measure, then, of the total amount of laser energy per unit area of exposed target tissue and is expressed as joules per square centimeter:

$$\text{RE} = \text{Power Density x Time}$$

The radiant exposure varies directly with the length of the exposure time. The exposure time can be varied by working in either the pulsed mode, with durations ranging from 0.05 to 0.5 seconds, or in the continuous mode.

In summary, the surgeon can control the CO_2 laser to incise, coagulate, or vaporize tissue by varying the power output, spot size or exposure time of the laser unit.

TISSUE EFFECTS

When electromagnetic energy (incident radiation) interacts with tissue, the tissue reflects part , the tissue absorps part, and the tissue transmitts and scatters part of the light. The surgical interaction of this radiant energy with tissue is caused only by that portion of the light that is absorbed (that is, the incident radiation minus the sum of the reflected and transmitted portions) (Polanyi, 1983).

The actual tissue effects produced by the radiant energy of a laser vary with the specific wavelength of the laser used. Each type of laser exhibits characteristic and different biological effects on tissue and is therefore useful for different applications. Yet, certain similarities exist regarding the nature of interaction of all laser light with biological tissue. The lasers used in medicine and surgery, today, can be ultraviolet where the interactions are a complex mixture of heating and photodissociation of chemical bonds. The more commonly used lasers emit light in the visible or the infrared region of the electromagnetic spectrum, and their primary form of interaction with biological tissue leads to heating. Therefore if the radiant energy of a laser is to exert its effect upon the target tissue, it must be absorbed by the target tissue and converted to heat (Fig. 7). Scattering tends spread the laser energy over a larger surface area of tissue, but limits the penetration depth (Fig. 8). The shorter the wavelength of light, the more it is scattered by the tissue. If the radiant energy is reflected from (Fig. 9) or transmitted through (Fig. 10) the tissue, no effect will occur. To select the most appropriate laser system for a particular application, the surgeon must have a thorough understanding of these four characteristics regarding the interaction of laser light with biologic tissue (Fuller, 1984).

The CO_2 laser creates a characteristic wound (Fig. 11). When the target absorbs a specific amount of radiant energy to raise its temperature to 60° to 65° C, protein denaturation occurs. Blanching of the tissue surface is readily visible and the deep structural integrity of the tissue is disturbed. When the absorbed laser light heats the tissue to approximately 100° C vaporization of intracellular water occurs. This causes vacuole formation, cratering and tissue shrinkage. Carbonization, disintegration, smoke and gas generation with destruction of the laser radiated tissue occurs at several hundred degrees centigrade. In the center of the wound is an area of tissue vaporization; here just a few flakes of carbon debris are noted. Immediately adjacent to this area is a zone of thermal necrosis measuring approximately 100 μm wide. Next is an area of thermal conductivity and repair, usually 300 to 500 μm wide. Small vessels, nerves, and lymphatics are sealed in the zone of thermal necrosis; the minimal operative trauma combined with the vascular seal probably account for the notable absence of postoperative edema characteristic of laser wounds (Mihashi et al., 1976).

Comparison studies have been performed with experimental animals on the histological properties of healing and the tensile strength of the healing wound following laser and scalpel produced incisions. Hall (1971) noted that the tensile strength in a CO_2 laser induced incision was less up to the twentieth day post-injury; by the fortieth day, however, it equaled that of the scalpel produced incision. Norris and Mullarry (1982) studied the healing properties of laser induced incisions on hogs and concluded that scalpel induced incisions exhibited better wound healing characteristics histologically up to the thirtieth day, after which time, both incisions exhibited similar results. Buell and Schuller (1983) compared the rate of tissue repair after CO_2 laser and scalpel incisions on hogs. In this study the tensile strength of the laser incisions was less than similar scalpel incisions

during the first 3 weeks after surgery; after that time rapid increases in the tensile strength of both wounds occurred at similar rates.

LASER TYPES AND APPLICATIONS

Six types of lasers are commonly in use in otolaryngology--head and neck surgery and many more are in various stages of development. These include the argon laser, the argon pumped tunable dye laser, Nd:YAG laser, KTP laser, flash lamp pumped dye laser, and CO_2 laser. The potential clinical applications of each of these surgical lasers are determined by their wavelength and specific tissue absorptive characteristics. Therefore, the surgeon should consider the properties of each wavelength when choosing a particular laser. This will facilitate the achievement of his surgical objective with minimal morbidity and maximal efficiency.

Argon laser

Argon lasers produce blue-green light in the visible range of the electromagnetic spectrum with primary wavelengths of .488 and .514 μm. The radiant energy of an argon laser may be strongly absorbed, scattered, or reflected, depending upon the specific biological tissues with which it interacts. Its extinction length in pure water is about 80 m (*extinction length* refers to the thickness of water necessary to absorb 90% of the incident radiation). Therefore the radiant energy from an argon laser is readily transmitted through clear aqueous tissues such as cornea, lens, and vitreous humor, and is absorbed and reflected to varying degrees by tissues white in color such as skin, fat, and bone. Light from an argon laser is absorbed by hemoglobin and pigmented tissues; a localized thermal

reaction takes place within the target tissue, causing protein coagulation. The clinician uses this selective absorption of the light from an argon laser to photocoagulate pigmented lesions such as port-wine stains, hemangiomas and telangiectasias (Apfelberg et al., 1981; Parkin and Dixon, 1981). Gradual blanching of the laser-photocoagulated tissue takes place over several months.

When the beam of the argon laser is focused to a small focal spot, its power density increases sufficiently to cause vaporization of the target tissue. This characteristic has allowed otologists to use this laser for the performance of stapedotomy procedures in patients with otosclerosis (Perkins, 1980). Bone, being a white tissue, reflects most of the incident radiation from an argon laser. Therefore, when performing an argon laser stapedotomy, it is necessary to place a drop of blood on the stapes to initiate absorption. Other applications of this laser in the middle ear include lysis of middle ear adhesions (DiBartolomeo and Ellis, 1980) and spot welding of grafts in tympanoplasty surgery (Escudero et al., 1979).

Argon tunable dye laser system

The argon tunable dye laser system works on the principle of the argon laser making a high intensity beam that is focused on dye that is continuously circulating in a second laser optically coupled with the argon laser. The argon laser beam energizes the dye, causing it to emit laser energy at a longer wavelength than the pump beam. By varying the type of dye and using a tuning system, different wavelengths can be obtained. The laser energy from this dye laser can then be transmitted through flexible fiberoptics and delivered through endoscopic systems or inserted directly into tumors. The major clinical use of this laser is with selective photodynamic therapy of malignant tumors following the intravenous

injection of the photosensitizer, hematoporphyrin derivative (Dougherty et al., 1975).

After the intravenous injection, the hematoporphyrin derivative disseminates to all the cells of the body, rapidly moving out of normal tissue, but remaining longer in neoplastic tissue. After a few days a differential in concentration exists between the tumor cells and the normal cells. When the tumor is exposed to red light (630 nm), the dye absorbs the light; the absorption of this red light causes a photochemical reaction to occur. Toxic oxygen radicals such as singlet oxygen are produced within the exposed cells causing selective tissue destruction and cellular death. Since there is less photosensitizer in the normal tissues, a much less severe or no reaction occurs. The main technical problem is getting enough light to the target area. Here, the argon tunable dye laser system has helped to solve this problem (Hayata et al. 1982). Additional research to increase the laser intensity and simplify the sometimes cumbersome setup is being conducted with gold vapor lasers and argon pumped titanium sapphire lasers (Petrucco et al., 1990).

Results obtained by many investigators in this country demonstrate that the premise of treating selected neoplasms with hematoporphyrin derivative followed by activation with red light is valid (Dougherty et al., 1978; Cortese and Kinsey, 1982; Wile et al., 1984a,b). The overall potential and exact place of maximum value of this form of treatment remain to be established. Areas that appear to be very promising include carcinoma of the urinary bladder (Tsuchiya et al., 1983), endobronchial lesions of the lung (Hayata et al., 1984), selected carcinomas of the upper aerodigestive tract (Wile et al., 1984a), skin cancers (McCaughan et al., 1983), and metastatic dermal breast cancers (Dougherty et al., 1979). Trials are now being conducted in certain specialties on intraoperative photodynamic therapy in conjunction with conventional surgery and on photodynamic therapy as the sole modality for the treatment of selected superficial mucosal carcinomas (Balchum et al.,

1984). The potential for this compound to serve as a tumor marker in sites where multicentric tumors are common, such as the mucosal surfaces lining the upper aerodigestive tract, has been recently discussed (Ossoff et al., 1984b). The use of a krypton laser with an image intensifier system to facilitate endoscopic detection of hematoporphyrin derivative fluorescence looks promising in the tracheobronchial tree (Dorion et al., 1984).

Nd:YAG laser

Nd:YAG lasers produce light with a wavelength of 1.064 μm in the near infrared (invisible) range of the electromagnetic spectrum. Pure water weakly absorbs the radiant energy of the Nd:YAG laser . The extinction length is about 40 mm. Therefore its radiant energy can be transmitted through clear liquids facilitating its use in the eye or other water filled cavities such as the urinary bladder. The absorption of light from this laser is slightly color dependent, with increased absorption in darkly pigmented tissues and carbonaceous debris. In biological tissue, strong scattering, both forward and backward, determines the effective extinction length, which is usually 2 to 4 mm. Back scattering can account for up to 40% of the total amount of scattering. The zone of damage produced by the incident beam of a Nd:YAG laser produces a homogeneous zone of thermal coagulation and necrosis that may extend up to 4 mm deep and lateral from the surface, making precise control impossible.

This laser is an excellent surgical instrument with which to perform tissue coagulation; vaporization and incision also can be performed with this wavelength. When used for these two functions, however, precision is lacking and tissue damage is wide spread.

The radiant energy from the Nd:YAG laser can be transmitted through flexible

fiberoptic delivery systems, allowing its use with flexible endoscopes. When used in the management of patients with obstructing neoplasms of the tracheobronchial tree, it is considered safer to use a rigid, ventilating bronchoscope, rather than a flexible fiberoptic bronchoscope (Dumon et al., 1984). With this approach, the laser fiber is passed down the lumen of the rigid bronchoscope with a rod lens telescope and suction catheter (Dumon et al., 1982). Otolaryngologists may begin to use this laser with the CO_2 laser when performing bronchoscopic laser surgery. The effective coagulating properties of the Nd:YAG laser should augment the predictable vaporizing properties of the CO_2 laser when treating patients with obstructive tracheal and proximal endobronchial cancers, especially when faced with an ulcerative or actively bleeding tumor (Ossoff, 1986).

CO_2 laser

CO_2 lasers produce light with a wavelength of 10.6 μm in the infrared (invisible) range of the electromagnetic spectrum. A second, built-in, coaxial helium neon laser is necessary to indicate with its red color the site where the invisible CO_2 laser beam will impact the target tissue. This laser, then, acts as an aiming beam for the invisible CO_2 laser beam. The radiant energy produced by the CO_2 laser is strongly absorbed by pure, homogeneous water and by all biological tissues high in water content. The extinction length of this wavelength is about 0.03 mm in water and in soft tissue; reflection and scattering are negligible. Because absorption of the radiant energy produced by the CO_2 laser is independent of tissue color, and because the thermal effects produced by this wavelength on adjacent nontarget tissues are minimal, the CO_2 laser has become extremely versatile for use in otolaryngology--head and neck surgery.

With current technology, light from this laser cannot be transmitted through existing flexible fiberoptic endoscopes, although research and development of a suitable flexible fiber for transmission of this wavelength is being carried out on an international level. Presently, the radiant energy of this laser is transmitted from the optical resonating chamber to the target tissue via a series of mirrors through an articulating arm to the target tissue (Ossoff and Karlan, 1985). This laser can be used free-hand for macroscopic surgery, attached to the operating microscope for microscopic surgery, and adapted to an endoscopic coupler for bronchoscopic surgery (Ossoff and Karlan, 1982); in this application, rigid, nonfiberoptic bronchoscopes must be used (Ossoff and Karlan, 1983b).

The CO_2 laser has become indispensable for the practice of laryngology, bronchology, neurootology, and pediatric otolaryngology. Many procedures in the upper aerodigestive tract that previously required prolonged hospitalization and tracheotomy can now be performed without the need for tracheotomy (Holinger, 1982), and often as an outpatient procedure. Within the field of neurootology and neurosurgery, recent reports have shown that the length of stay and perioperative morbidity associated with laser removal of acoustic neuromas is reduced when compared to conventional techniques (Cerullo and Mkrdichian, 1987).

In the oral cavity, benign tumors can be excised with the laser (McDonald and Simpson, 1983). A one-stage tongue release can be performed for patients requiring rehabilitation of speech following composite resection with tongue flap reconstruction (Liston and Giordano, 1981). Multiple areas of leukoplakia can be precisely excised; often, a graft is not necessary to resurface the operative field. Selected superficial carcinomas can be precisely excised with the use of the laser, and large recurrent or inoperable tumors can be debulked for palliation (Strong et al., 1979).

The laser has also been used in the management of nasal and paranasal sinus disease; choanal atresia (Healy et al., 1978), hypertrophic inferior turbinates (Mittelman, 1982), squamous papilloma and hereditary hemorrhagic telangiectasia have been treated with the CO_2 laser (Simpson et al., 1982). Yet, the argon laser is a more efficacious instrument for the treatment of hereditary hemorrhagic telangiectasia.

Facial plastic surgical applications where the CO_2 laser has shown promise include the excision of rhinophyma (Shapshay et al., 1980), the excision of benign and malignant skin tumors (Kirschner, 1984), and the vaporization and excision of nevi and tattoos (Levine and Balin, 1982).

The CO_2 laser has found its greatest use in otolaryngology--head and neck surgery in the microscopic surgical management of benign and malignant diseases of the larynx. Surgery for recurrent respiratory papillomatosis has advanced with the use of the laser. The increased ability to preserve normal laryngeal structures while maintaining the translaryngeal airway more than offsets the initial disappointment associated with the laser's inability to cure the disease (Simpson and Strong, 1983). In the pediatric patient population, surgery for webs, subglottic stenosis, capillary hemangiomas and other space occupying airway lesions has been significantly improved by the precision, preservation of normal tissue, and predictable minimal amount of postoperative edema associated with the judicious use of the CO_2 laser (McGill et al., 1983).

In adults, surgery for polyps, nodules, leukoplakia, papilloma, cysts, granulomas, and other benign laryngeal conditions can be performed effectively with the laser (Vaughan, 1983). A new era of conservation surgery or phonosurgery for benign laryngeal disease has been created by the laser. In the past, microlaryngeal surgery for benign disease has been mucosal stripping with healing by remucosalization. Now, normal mucosal tissue can

be preserved by elevating and advancing mucosal flaps with new endoscopic laser techniques (Karlan and Ossoff, 1984). The addition of the microspot micromanipulator has furthered these techniques (Shapshay et al., 1988; Ossoff et al., 1991).

The addition of the CO_2 laser to endoscopic arytenoidectomy allows the surgeon to precisely vaporize the mucosa and underlying arytenoid cartilage layer by layer in a dry field (Ossoff et al., 1984a). The precision associated with the use of the laser facilitates performance of this operation even by surgeons who had difficulty mastering the conventional techniques of endoscopic arytenoidectomy (Thornell, 1984).

The transoral management of squamous cell carcinoma of the larynx using the CO_2 laser is an obvious extension of the application of this surgical instrument. The advantages of precision, increased hemostasis, and decreased intraoperative edema allow the surgeon to perform exquisitely accurate and relatively bloodless endoscopic surgery of the larynx. Recent reports have shown that determinate cure rates with this method of management are equivalent to radiotherapy (Blakeslee et al., 1984; Koufman, 1986).

Bronchoscopic indications for CO_2 laser surgery include management of recurrent respiratory papillomatosis or granulation tissue within the tracheobronchial tree, excision of selected subglottic or tracheal strictures, excision of bronchial adenomas and reestablishment of the airway in patients with obstructing tracheal or endobronchial cancers. In this latter instance, palliation or reduction of the patient's symptoms of airway obstruction or hemoptysis is the desired goal (Ossoff et al., 1986).

KTP laser

The potassium titanyl phosphate (KTP) laser has been recently introduced for surgery. It lases at 532 nm, and therefore compares with the argon laser. The scattering

and absorption by skin pigments are nearly the same as the argon laser. Yet, the KTP laser light is more strongly absorbed by hemoglobin. The KTP laser has shown success with stapedotomies (Bartels, 1990). Thedinger (1990) has promoted the KTP for chronic ear surgery. He specifically identifies the removal of hyperplastic infected mucosa, disarticulating mobile stapes suprastructure in a complete cholesteatoma removal and the removal of previously inserted middle ear implants. The KTP crystal actually frequency doubles (halves the wavelength) of a Nd:YAG laser. Therefore, this laser usually allows one to switch the output between the 532 nm KTP light and the 1064 nm Nd:YAG light.

Flash lamp pumped dye laser

The treatment of hemangiomas and port wine stains with lasers has benefitted from the application of the flash lamp pumped dye laser. The dye was initially selected for maximum absorption by the oxyhemoglobin at 577 nm. A study by Tan et al., (1990a) showed that at 585 nm there is maximal hemoglobin absorption with a minimum of scattering and minimal absorption by melanin and other pigments. The light pulse is about 400 μsec long to minimize thermal diffusion in the tissue. Although dark Negroid skin types show little or no selective vascular photothermolysis with the laser, the results with lighter skin are significant. At a threshold dose, specific vascular injury is observed without the disruption of the adjacent tissue in lightly pigmented skin (Tan, et al., 1990b).

Other lasers

In an effort to have a more controlled laser effect with less damage to adjacent tissue, several lasers in the near to mid infrared region have been investigated. These include the

erbium:YAG (Er:YAG) and the holmium:YAG (Ho:YAG). The Er:YAG lases at the infrared peak of water absorption at 2.94 μm. Here the extinction length in water is less than 2 μm. The laser produces very clean incisions with a minimal amount of thermal damage to the adjacent tissue. There are two negative aspects to this laser: The wavelength is too long to be transmitted through normal optical fibers. This gives a distinct advantage to lasers that produce light that can be transmitted through fibers. More importantly, the thermal propagation is so short there is practically no tissue coagulation and no hemostasis. This laser is therefore unsuitable of use in highly vascular tissue.

The Ho:YAG laser operates at 2.1 μm. This wavelength can be effectively transmitted through fibers. The extinction length is water is about 0.4 mm, which suggests that this laser light should interact with tissue very similar to the CO_2 laser. The Ho:YAG has been combined with fiberoptic endoscope for sinus surgery (Schlenk et al., 1990). The hemostasis is good and the soft bone ablation is readily controlled. Adjacent thermal damage zones varied from 130 to 220 μm in a study by Stein et al., (1990).

There is also work with other materials that lase in the near infrared region of the spectrum, such as the cobalt:magnesium fluoride laser (tunable from 1.8 to 2.14 μm). Alexandrite lasers (750 nm) and titanium sapphire lasers (tunable from 0.6 to 1.0 μm) have also been considered. Ultimately, many parameters such as cost, reliability and size, in addition to the tissue response, will influence choice of lasers in medicine.

PULSE STRUCTURE

In the section on the **Control of the Surgical Laser** it was pointed out that the surgeon has three parameters to select when using a particular laser. The intensity of the

laser is the least useful. The exposure time is important in that it controls the total amount of light incident on the tissue, the Radiant Exposure. The pulse structure of the laser light within the given exposure time is also crucial. The pulse structure is a characteristic of the lasing medium and the cavity configuration. It is often fixed and the surgeon cannot change or modify it.

Many lasers operate in a continuous wave (cw) mode. In this mode, the laser is always on. The instantaneous intensity and the average laser intensity are essentially the same. A shutter, external to the laser cavity, usually controls the exposure time. This allows the laser to operate independent of the exposure time or the frequency of exposures. This gives the most stable operation. A surgical CO_2 or Nd:YAG laser will operate cw at intensities of a few watts to more than 50 W.

Certain lasers operate in a pulsed mode. Flash lamp pumped lasers can pulse from about 0.5 μs to several 100 ms. The first Ruby laser operated in a pulsed mode. The flashlamp used to pump the ruby crystal had about a 1 msec pulse duration. It was clear that the laser output of this first laser was irregular and unstable. Observing the output with a fast detector and oscilloscope, the output intensity was not a millisecond long laser pulse, but it observed to be a series of irregular spikes. Each spike was a few microseconds long and there were several microseconds between the spikes. The stimulated emission in the ruby is so efficient, that it quickly depletes the population inversion, and the lasing stops. After the lasing stops the flashlamp can reestablish tthe population inversion. The lasing can then resume. The process repeats until the flash lamp stops. Most of the long pulsed lasers operate in a spiking mode.

The spiking of the laser output can be controlled to produce a single very short laser pulse, much shorter than the flashlamp lifetime. One technique to produce the short pulses

is *Q-switching*. Here, the laser pumping process (usually a flash lamp) builds up a large population inversion inside the laser cavity. The laser is prevented from lasing by blocking or removing one of the mirrors. After a large population inversion has developed the feedback is restored, and a short intense burst of laser light depletes the accumulated population inversion in typically 10 to 50 ns. Q-switching can be accomplished by several different methods. The most direct and earliest method used was rotating the end mirror so that lasing could take place during the short interval when the mirror was correctly aligned. Waring blender motors were often used as a fast, stable motors. However, uncertain timing, lack of reliability and vibration (not to mention the noise) lead to many problems, particularly with the alignment. Electrooptic polarization rotators and acoustooptic beam deflectors are now commonly used for Q-switching.

Cavity dumping produces slightly shorter pulses of light. In this technique, the laser is pumped and allowed to lase between completely reflecting mirrors. The light energy is trapped in the cavity until it reaches a maximum. Then one of the mirrors is "removed" from the cavity and allows all the light to leave the cavity. The laser pulse has a physical length of twice the cavity length. The time duration of the laser pulse is then $2l/c$ where l is the length of cavity and c is the speed of light ($c \sim 3 \times 10^{10}$ cm/s or $c \sim 1$ ft/ns).

Mode locking produces pulses of light as short as a few ps. A Q-switched laser operates in several longitudinal modes (or slightly shifted frequencies). A fast saturable dye brings all these modes into phase. The nanosecond macro pulse of light is actually a train of micro pulses. Each micro pulse in the train is several picoseconds long and repeats at about 100 MHz. These pulses can be further compressed by various compression techniques. The shortest laser light pulses achieved in the laboratory are less than 4 wave oscillations long (~6 fs).

The pulsed laser dramatically changes the interactions of the light with tissue. The intensity of the laser during the pulse is extremely high (approaching 10^9W). The high intensity and short pulse duration enables the laser light efficiently to ablate tissue before the thermal energy spreads by thermal diffusion. The pulse needs to be significantly shorter than the thermal diffusion times to prevent thermal diffusion from spreading damage. Typically, a tissue under laser irradiation reaches thermal equilibrium within a few milliseconds. The heat will spread over several micrometers in less than 10 μsec (Reinisch, 1989). Also, the transverse mode structure of the laser beam must be preserved in the short pulses to yield the small focal spot size.

SAFETY CONSIDERATIONS

Education

The laser is a precise but potentially dangerous surgical instrument that must be used with caution. While certain distinct advantages are associated with the use of this relatively new technology in the management of certain benign and malignant diseases of the upper aerodigestive tract, these advantages must be weighed against the possible risks of complications associated with laser surgery. Because of these risks, the surgeon must first determine if the use of the laser affords an advantage over conventional surgical techniques. For the surgeon to exercise this required good judgement in the selection and use of lasers in his practice, prior experience in laser surgery is necessary. Therefore exposure to some type of formal laser education program has to be a prerequisite to the use of this technology. The surgeon who has not received training in laser surgery as a resident should attend one of the many excellent hands-on training courses in laser surgery given in this country. Such a course should include laser biophysics, tissue interactions, safety

precautions, and supervised hands-on training with laboratory animals. Following completion of such a course, the surgeon should practice laser surgery on cadaver or animal specimens before progressing to the more simple procedures on patients.

Each hospital performing laser surgery should appoint a laser safety officer and set up a laser safety committee consisting of the laser safety officer, two or three physicians using the laser, one or two nursing representatives from the operating room, a hospital administrator, and a biomedical engineer. The purpose of this committee is to develop policies and procedures for the safe use of lasers within the hospital. As such, the safety protocols that will be established by this committee will vary with each specialty and use of the laser. In addition, the laser safety committee should make recommendations regarding the appropriate credential-certifying mechanisms required for physicians and nurses to become involved with each laser. Educational policies for surgeons, anesthesiologists, and nurses working with the laser should be developed. Other responsibilities of this important committee include the accumulation of laser patient data in cases where an investigational device was used and a periodic review of all laser related complications.

Suggested minimal educational requirements for surgeons to use lasers are discussed above. Because the anesthesiologist is also concerned with the airway and because potent oxidizing gases pass through the airway in close approximation to the path of the laser beam, it is necessary to develop a team approach to the anesthetic management of the patient undergoing laser surgery of the upper aerodigestive tract. Therefore, it is highly recommended that the anesthesiologists involved with laser surgery cases attend a didactic session devoted to that subject. Finally, the operating room staff must receive some education with regard to laser surgery. Attendance at an in-service workshop with exposure to clinical laser biophysics and the basic workings of the laser as well as hands-on

orientation should be the minimal requirement for nursing participation in laser surgery cases (Spilman, 1983).

Safety protocol

Development of an effective laser safety protocol that stresses compliance and meticulous attention to detail by the surgeon, anesthesiologist, and operating room nurse (laser surgery team) is probably the single most important reason this potentially dangerous surgical instrument can be used so safely in treating patients with diseases of the upper aerodigestive tract (Ossoff, 1989). Such a laser safety protocol is usually general enough to list all the major and most minor precautions necessary when laser surgery is being performed in the specialty of otolaryngology--head and neck surgery. General considerations concern the provision for protection of the eyes and skin of patients and operating room personnel, as well as the provision for adequate laser plume (smoke) evacuation from the operative field. Additional precautions concern the choice of anesthetic technique, the choice and protection of endotracheal tubes, and the selection of proper instruments, including bronchoscopes.

Eye protection

Depending on the wavelength, corneal or retinal burns, or both, are possible from acute exposure to the laser beam. The possibility for corneal or lenticular opacities (cataracts) or retinal injury exists following chronic exposure to excessive levels of laser radiation. Several different structures of the eye are at risk; the area of injury usually depends upon which structure absorbs the most radiant energy per volume of tissue. Retinal effects occur when the laser emission wavelength occurs in the visible and

near-infrared range of the electromagnetic spectrum (0.4 to 1.4 μm). When viewed either directly or secondary to reflection from a specular (mirror-like) instrument surface, laser radiation within this wavelength range would be focused to an extremely small spot on the retina, causing serious injury. This occurs because of the focusing effects of the cornea and lens. Laser radiation in the ultraviolet (less than 0.4 micrometers) or in the infrared range of the spectrum (greater than 1.4 micrometers) produce effects primarily at the cornea, although certain wavelengths also may reach the lens ("American National Standard," 1981).

To reduce the risk of ocular damage during cases involving the laser, certain precautions should be followed. Protection of the eyes of the patient surgeon and other operating room personnel must be addressed; the actual protective device will vary according to the wavelength of the laser used. A sign should be placed outside the operating room door warning all persons entering the room to wear protective glasses because the laser is in use. In addition, extra glasses for the specific wavelength in use at the time should be placed on a table immediately outside the room. The doors to the operating room should remain closed during laser surgery with the CO_2 laser, and locked when working with the Nd:YAG or argon laser.

For patients undergoing CO_2 laser surgery of the upper aerodigestive tract, a double layer of saline moistened eye pads should be placed over the eyes. All operating room personnel should wear protective glasses with side protectors. Regular eyeglasses or contact lenses protect only the areas covered by the lens and do not provide protection from possible entry of the laser beam from the side. When working with the operating microscope and the CO_2 laser, the surgeon need not wear protective glasses; here the optics of the microscope provide the necessary protection (Ossoff et al., 1983a).

When working with the Nd:YAG laser, all operating room personnel must wear wavelength specific protective glasses that are usually of a blue/green color. The patient's eyes also should be protected with a pair of these glasses. Though it may appear that the beam direction and point of impact are confined within the endoscope, inadvertent deflection of the beam may occur due to a faulty contact, a break in the fiber, or accidental disconnection between the fiber and endoscope. Special wavelength-specific filters are available for flexible and rigid bronchoscopes; when these filters are in place, the surgeon need not wear protective glasses ("Guide," 1984).

When working with the argon, KTP, or dye lasers, all personnel in the operating room, including the patient, should again wear wavelength specific protective glasses, which are usually of an amber color. When performing photocoagulation procedures for selected cutaneous vascular lesions of the face, protective metal eye shields rather than protective glasses are usually used on the patient (DiBartolomeo, 1981). Similar precautions are necessary for the newer visible and near infrared wavelength lasers. The major difference is the type of eye protection that is worn.

Skin protection

All exposed skin and mucous membranes of the patient outside the surgical field should be protected by a double layer of saline saturated surgical towels, surgical sponges, or lap pads. When microlaryngeal laser surgery is being performed, the possibility exists that the beam might partially reflect off the proximal rim of the laryngoscope, rather than go down it. So, saline saturated surgical towels completely drape the patient's face; only the proximal lumen of the laryngoscope is exposed. Great care must be exercised to keep the wet draping from drying out; it should be moistened from time to time during the case.

Teeth in the operative field also need to be protected; saline saturated telfa, surgical sponges, or specially constructed metal dental impression trays can be used. Meticulous attention is paid to the protective draping procedures at the beginning of the surgery; the same compulsion should be displayed for the continued protection of the skin and teeth during the surgical procedure (Ossoff et al., 1983a).

Smoke evacuation

Two separate suction setups should be available for all laser cases in the upper aerodigestive tract; one provides for adequate smoke and steam evacuation from the operative field, while the second is connected to the surgical suction tip for the aspiration of blood and mucous from the operative wound (Spilman, 1983). When performing laser surgery with a closed anesthetic system, constant suctioning should be used to remove laser-induced smoke from the operating room; this helps to prevent inhalation by the patient, surgeon or operating room personnel. When the anesthetic system used is an open one or with jet ventilation systems, suctioning should be limited to an intermittent basis to maintain the forced inspiratory oxygen (FIO_2) at a safe level. Laryngoscopes, bronchoscopes, operating platforms, mirrors, and anterior commissure and ventricle retractors with built-in smoke evacuating channels facilitate the easy evacuation of smoke from the operative field (Ossoff and Karlan, 1983a). A recent report has suggested that the smoke created by the interaction of the CO_2 laser with tissue is probably mutagenic (Tomita et al., 1981). Filters in the suction lines should be used to prevent clogging by the black carbonaceous smoke debris created by the laser (Mohr et al., 1984).

Anesthetic considerations

Optimal anesthetic management of the patient undergoing laser surgery of the upper aerodigestive tract must include attention to the safety of the patient, the requirements of the surgeon, and the hazards of the equipment. Because of the length of time required to expose the larynx and suspend the laryngoscope, manipulate the operating microscope into position, and accurately align the laser beam down the center of the long axis of the laryngoscope, most patients require general anesthesia for this type of surgery. Any nonflammable general anesthetic is suitable; halothane and enflurane are most often used. Because of the risk of fire associated with general endotracheal anesthesia, the inspired concentration of oxygen, a potent oxidizing gas, is important. Mixtures of helium, nitrogen, or air plus oxygen are commonly used to maintain the FIO_2 around but not above 40% and insure that the patient is adequately oxygenated. Nitrous oxide is also a potent oxidizing gas; and should not be used in the anesthetic mixture to cut the oxygen concentration. When performing laser surgery in the tracheobronchial tree through the rigid, ventilating bronchoscope, 100% oxygen may be used. In either case, intravenous supplementation with small doses of narcotics and/or tranquilizers is often used to shorten the emergence period following anesthesia. Muscle relaxation is required to prevent movement of the vocal cords when working in the larynx. Jet ventilation techniques during laser surgery work well for selected patients (Edelist and Alberti, 1982); the present unavailability of a satisfactory method of total intravenous anesthesia has limited its widespread use in complicated cases, or those requiring multiple frozen-section examinations.

At the present time a nonflammable, universally accepted endotracheal tube for laser surgery of the upper aerodigestive tract does not exist. The polyvinyl endotracheal tube should not be used, either wrapped or unwrapped. It offers the least resistance to penetration by the laser beam of all the endotracheal that have been tested, and

fire-breakdown products and tissue destruction associated with combustion of this tube are the most severe. The Rusch red rubber tube offers some resistance to penetration by the laser beam and causes mild to moderate damage to the tracheobronchial tree should a fire occur. The silicone tube offers more resistance to penetration than the red rubber tube; however, silica ash can be seen in the airway after fires with these tubes and raises the possibility of future problems with silicosis (Ossoff et al., 1983b). Although the Norton metal tube (Norton and DeVos, 1978) is nonflammable, problems with rigidity, inner-to-outer diameter ratios, gas leakage, and lack of a cuff have prevented it from becoming the universally accepted tube of choice for CO_2 laser surgery. Newer endotracheal tubes for laser surgery (wavelength specific) are now available from several manufacturers.

Protection of the endotracheal tube from either direct or reflected laser beam irradiation is of primary importance. Should the laser beam strike an unprotected endotracheal tube carrying oxygen, ignition of the tube could result in a catastrophic, intraluminal, blow-torch type endotracheal tube fire (Schramm et al., 1981). Red rubber endotracheal tubes wrapped circumferentially from the cuff to the top with reflective metallic tape reduces the risk of intraluminal fire when a special laser protective endotracheal tube cannot be used Metallic tape covered with merocel™ is another acceptable alternative. Mylar tape offers no protection from the laser and should not be used (Ossoff and Karlan, 1984b).

Protection also needs to be provided for the cuff of the endotracheal tube. Methylene blue-colored saline should be used to inflate the cuff (Ossoff et al., 1983a). Saline-saturated neurosurgical cottonoids are then placed above the cuff in the subglottic larynx to further protect the cuff. These cottonoids require frequent moistening during the procedure. Should the cuff become deflated from an errant hit by the laser beam, the

already-saturated cottonoids would turn blue to warn the surgeon of impending danger. The tube should then be removed and replaced with a new one. Use of the operating platform is strongly recommended as a further insulation against potential danger. Inserted into the subglottic larynx above the level of the packed cottonoids, this unique instrument serves as a catcher's mitt to protect the cottonoids, endotracheal tube and cuff from any direct or reflected laser beam irradiation (Ossoff and Karlan, 1984a).

The Nd:YAG laser has a different interaction with endotracheal tubes than the CO_2 laser. *In vitro* testing of various endotracheal tubes with the Nd:YAG laser has demonstrated that the safest tube to use is a colorless or white polyvinyl endotracheal tube or silicone endotracheal tube without any black or dark colored lettering on the tube itself. Also, the tube should not have any lead-lined marking. The Rusch red rubber tube with or without metallic tape did not protect against ignition with the Nd:YAG laser (Shapshay, no date).

Instrument selection

The surface characteristics of instruments used in laser surgery should provide for low specular or direct reflectance and large diffuse or scattered reflectance of the laser beam, should the beam inadvertently strike the instrument. Plastic instruments should be avoided since they can melt with the laser irradiation. Use of instruments with these surface characteristics will contribute to minimizing tissue injury or endotracheal tube ignition from direct or reflected laser beam irradiation.

Rigid instrumentation is the preferred method of laser bronchoscopy with either the CO_2 or Nd:YAG laser; should active bleeding occur during a case, it would be extremely difficult or impossible successfully to control the airway and evacuate the blood using

flexible instrumentation. Additionally, rigid instrumentation allows the surgeon to pass one, two, or three suction cannulas through the bronchoscope to facilitate blood evacuation and airway control. This point must be emphasized because of the recent proliferation of the Nd:YAG laser surgery and the ability of this laser light to be delivered through flexible fiberoptic endoscopes as well as rigid endoscopes.

Bronchoscopic couplers for CO_2 laser surgery must have an optical system that allows the visible helium-neon aiming laser beam to be passed coaxially with the invisible CO_2 laser beam. In addition, the surgeon should be able to center the beam within the lumen of the bronchoscope to avoid the hazards of the beam reflecting off the inside wall of the bronchoscope, with subsequent loss of power and possible heating of the bronchoscope itself. Burns of the trachea, larynx, pharynx, and oral cavity have occurred as a direct result of such an event (Ossoff and Karlan, 1983b).

Effectiveness of a safety protocol

Strong and Jako (1972) and later Snow et al. (1976) warned of the possible complications associated with laser surgery of the upper aerodigestive tract including the risks of endotracheal tube fires and tissue damage from reflection of the laser beam. Following these early warnings, several reports of complications uniquely attributable to use of the CO_2 laser appeared in the literature (Alberti, 1981; Burgess and Lejeune, 1979; Cozine et al., 1981; Meyers, 1981). In a survey of laser-related complications reported by Fried (1984), 49 of 152 otolaryngologists who used the laser reported 81 complications that included 28 separate incidents of endotracheal tube fires. A recent analysis of complications unique to the use of the laser that occurred under a rigid safety protocol at Northwestern University Medical School and affiliated hospitals revealed a 1.7% incidence

of complications; no fires were reported in this group (Ossoff et al., 1983). Healy et al. (1984) published a 0.2% complication rate in 4416 cases of CO_2 laser surgery in the upper aerodigestive tract. Ossoff (1989) published an extensive review of laser-related complications experienced by 218 past registrants of hands-on laser surgery training courses that he directed. Seven surgeons experienced 8 complications and no endotracheal tube fires. The complication rate was 0.1% in over 7200 laser surgical procedures. The conclusions of these papers are similar. First, certain precautions are necessary when performing laser surgery of the upper aerodigestive tract. Second, adherence to a rigid safety protocol allows laser surgery of the airway to be preformed safely and with an extremely small risk of serious complications.

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FIGURE LEGENDS

Figure 1: The interaction of light (a photon) with an atom. Three processes are shown: the absorption of a photon by an atom in a low energy state, the spontaneous emission of a photon from an atom in an excited state, and the stimulated emission of a photon by a second photon of the same wavelength from an excited state atom.

Figure 2: The optical resonating chamber of a CO_2 laser. The gas molecules are excited by an electric current. The gas is cooled by a water jacket. The two mirrors provide the optical feedback for the amplification. The emitted light is coherent, monochromatic and collimated. The light can be focussed to a small point with an external lens.

Figure 3: (a) Laser-tissue interaction when the tissue is the focal distance away from the lens. Note the minimum beam diameter in the focal plane. (b) Laser-tissue interaction when the tissue is not in the focal plane of the lens. The laser covers a much larger area on the tissue surface.

Figure 4: (a) Light emitted from a conventional lamp. The light travels in all directions, is composed of many wavelengths and the light is not coherent. (b) Light emitted from a laser. The light all travels in the same direction, it is a single wavelength and all of the waves are in phase (the light is coherent).

Figure 5: The beam waist of parallel light focussed by a lens. The focal length of the lens

is *f*, the incident beam is TEM_{00} and has a diameter incident on the lens of D. The beam waist has a diameter of d.

Figure 6: Schematic graph of power density vs. spot size. The ratios are arbitrary for a current model CO_2 laser. The cylinder height represents the amount of tissue vaporized after a one second exposure at the three designated focal lengths.

Figure 7: Schematic illustration of absorption.

Figure 8: Schematic illustration of scattering.

Figure 9: Schematic illustration of reflection.

Figure 10: Schematic illustration of transmission.

Figure 11: Schematic illustration of the wound created by the carbon dioxide laser, showing the representative zones of injury.

OUTLINE

I. INTRODUCTION

II. LASER BIOPHYSICS

III. CONTROL OF THE SURGICAL LASER

IV. TISSUE EFFECTS

V. LASER TYPES AND APPLICATIONS

- A. Argon laser
- B. Argon tunable dye laser system
- C. Nd:YAG laser
- D. CO_2 laser
- E. KTP laser
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VI. PUSLE STRUCTURE

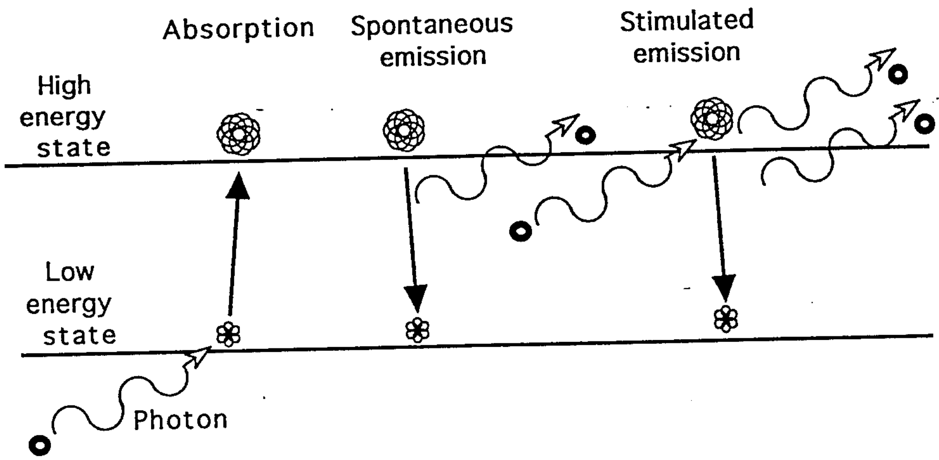
VII. SAFETY CONSIDERATIONS

- A. Education
- B. Safety protocol
- C. Eye protection
- D. Skin protection
- E. Smoke evacuation
- F. Anesthetic considerations
- G. Instrument selection
- H. Effectiveness of a safety protocol

VIII. REFERENCES

Figure Summary Sheets

Laser Surgery: Ossoff and Reinisch



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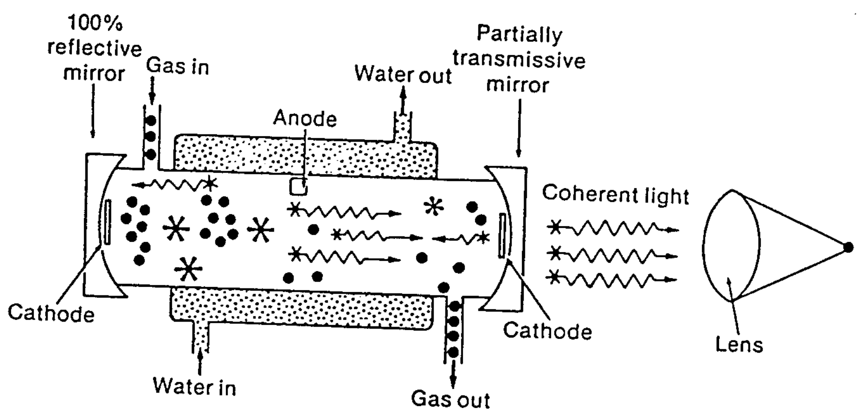

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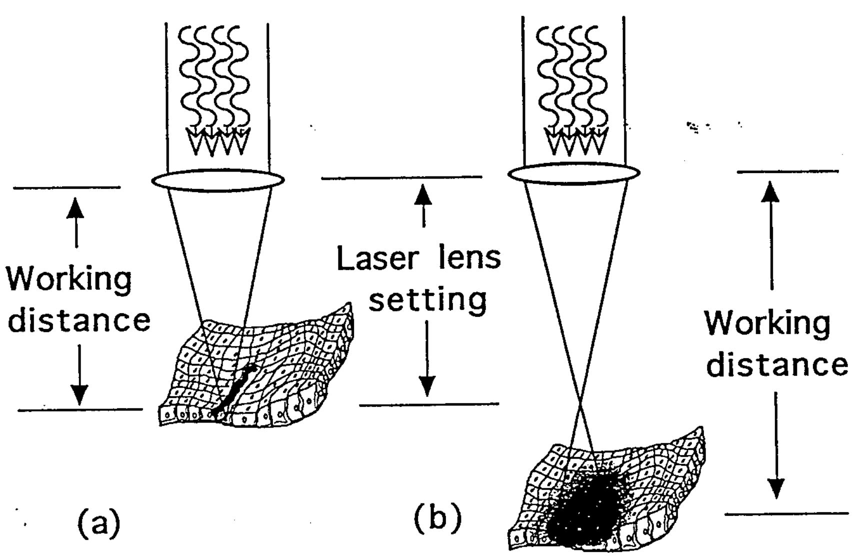
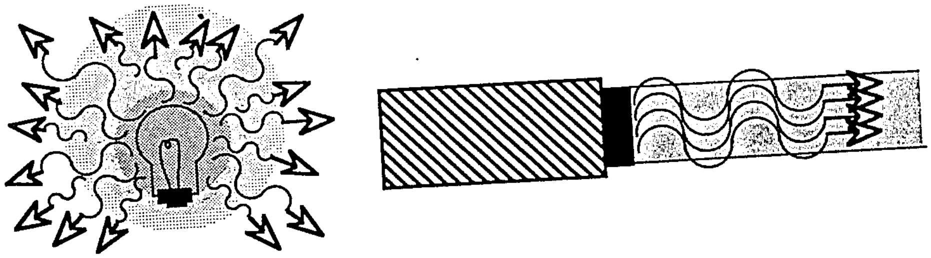


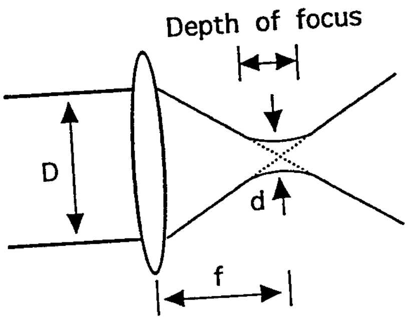
Figure 3

Ossoff & Reinisch



(a) (b)

Figure 4



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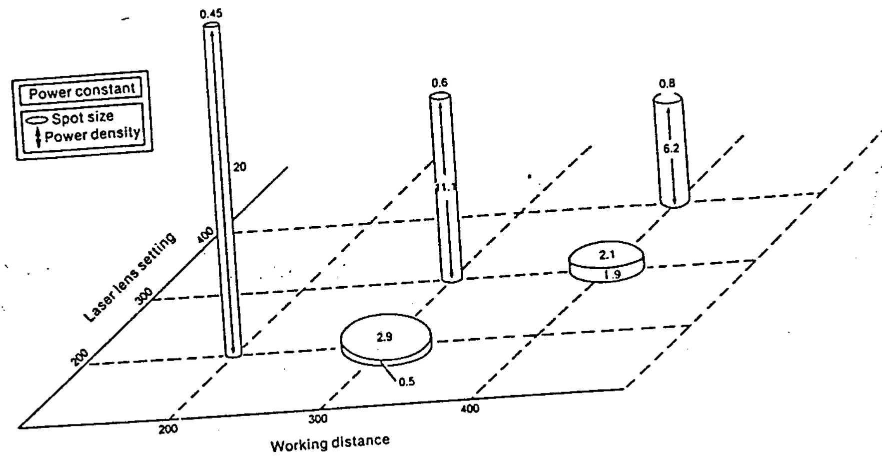

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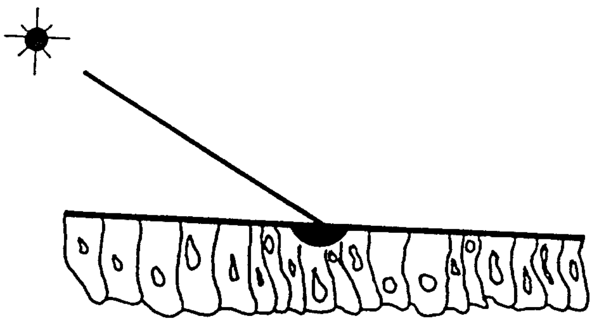

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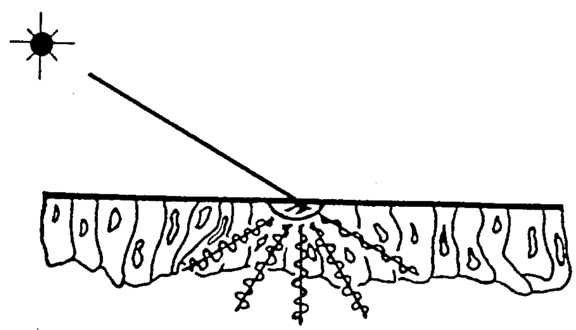

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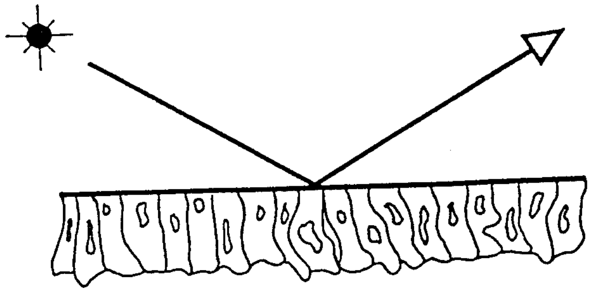

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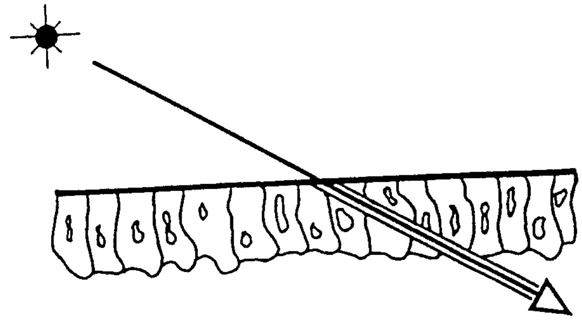

Figure 10

OSSOFF AND REINISCH

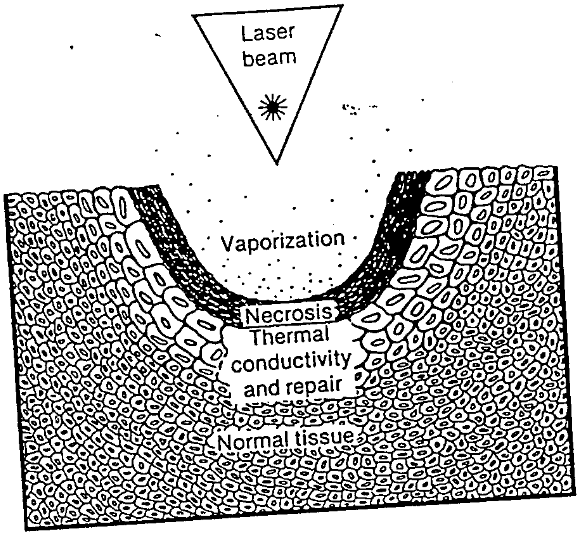

FIGURE 11